

## STONECUTTERS BRIDGE, HONG KONG DESIGN AND CONSTRUCTION

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### Abstract

*Stonecutters Bridge is a large cable stayed road bridge spanning the Rambler Channel in Hong Kong above one of the world's busiest shipping channels. The concept design was procured by Hong Kong Highways Department through an international design competition in 2000. Design challenges included quantifying the effects of a turbulent wind climate on the flexible structure, as well as many other detailed investigations, tests and analyses.*

*Construction commenced in early 2004. Site activities have all been large scale, including deep large diameter piles, large in-situ concrete pours, massive temporary works, high level working, and heavy lifting operations. Geometry of steelwork fabrication and erection had to be carefully controlled. The final main span segment was lifted into place in March 2009. Opening is scheduled for the end of the year.*

**Keywords:** Stonecutters Bridge, wind climate, ship impact, seismic design, construction, heavy lift, stay cables

## 1. INTRODUCTION

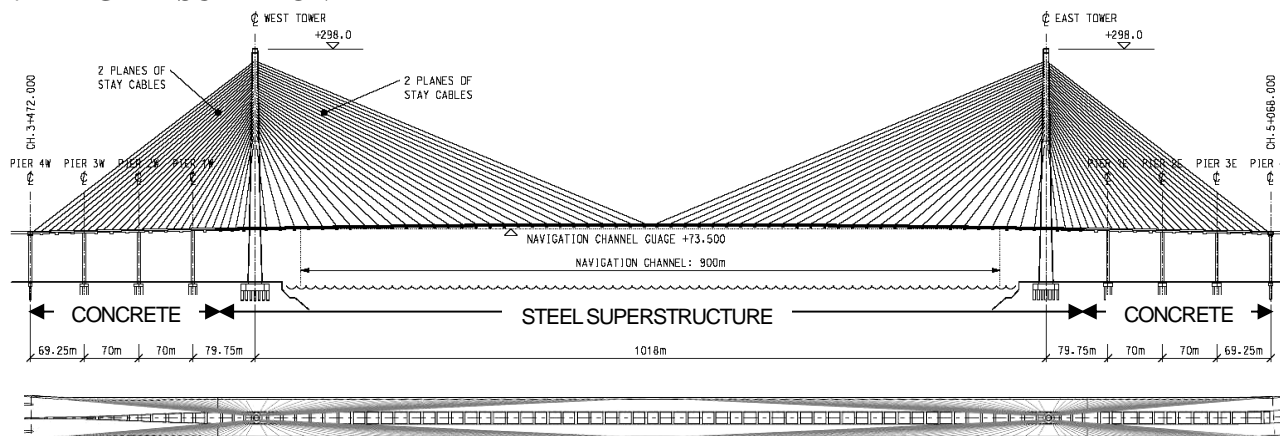
Stonecutters Bridge is part of Hong Kong's Route 8 - a new east-west expressway providing a further link between Sha Tin and Tsing Yi Island. The dual 3-lane road provides an alternative option on the route to the Hong Kong international airport off Lantau Island and better access connections into the container terminals at Kwai Chung. The bridge spans the Rambler Channel, providing high level clearance and linking container terminal 8 on Stonecutters Island on the east side to the new container terminal 9 on Tsing Yi Island on the west.



<Fig. 1> Location of Stonecutters Bridge

Highways Department of Hong Kong (HyD) procured the bridge concept through an international design competition in 2000. The consultancy for the detailed design, awarded to Arup and COWI in March 2001, started with a thorough technical review of the competition winning concept. Detailed design [1] commenced in March 2002, with particular studies [2] carried out into wind, seismicity and ship impact as part of the design process. The construction contract was awarded to the Maeda - Hitachi - Yokogawa - Hsin Chong joint venture (MHYHJV) in April 2004. Throughout construction many interesting challenges have been overcome [3], [4], [5]. This paper summarises the design and construction processes involved in creating this ground breaking long span cable-stayed bridge.

## 2. BRIDGE DESCRIPTION



<Fig. 2> Elevation and Plan

Stonecutters Bridge is cable-stayed with a steel main span of 1018m, and a total length of 1596m. There are four prestressed concrete back spans on each side. The tapered mono-towers are in concrete up to level +175m and steel-concrete composite from level +175m to level +293m with the outer steel skin being duplex stainless steel. 5m tall glazing structures top the towers off to level +298m. The 2 planes of stay cables take a modified fan arrangement, anchored at the outer edges of the deck at 18m intervals in the main span and 10m intervals in the back spans.

The deck is a twin box-girder, with the two longitudinal girders connected by cross girders. The piers in the back spans are monolithically connected to the deck. The three intermediate piers are single column piers, while the end piers at the adjoining viaducts are twin column portal structures. Laterally the bridge deck is restrained by vertical bearings on the towers and by the back span piers. In the longitudinal direction dynamic movements are restrained by hydraulic buffers at the towers. The ground is reclaimed on both sides, and comprises a highly variable thickness of superficial deposits overlying bedrock typically at level -50m to -90m.

## 3. DETAILED DESIGN

The bridge was the first cable-stayed bridge with a span over 1km for which detailed design was completed. The exposure of the site to typhoon winds created particular challenges, as did the busy harbour, which imposes severe restrictions on the construction operations. The bridge will carry traffic with a very high content (around 42%) of heavy goods vehicles.

### 3.1 Design Criteria

The design criteria are summarised in a Design Memorandum and are based on the Hong Kong Structures Design Manual for Highways and Railways issued by HyD, supplemented by BS5400 and other relevant codes. However, a number of investigations were carried out to establish site-specific design loads from wind, seismic activities and accidental ship impact.

### 3.2 Design for Extreme Events

#### Wind Loading

The wind dominated the design. The bridge is a large highly flexible structure and required a complete wind model for dynamic calculations. Wind turbulence intensity measurements were made near the bridge site to measure the site specific wind conditions. This helped to calibrate and supplement the results from a 1:1500 scale wind tunnel model of the

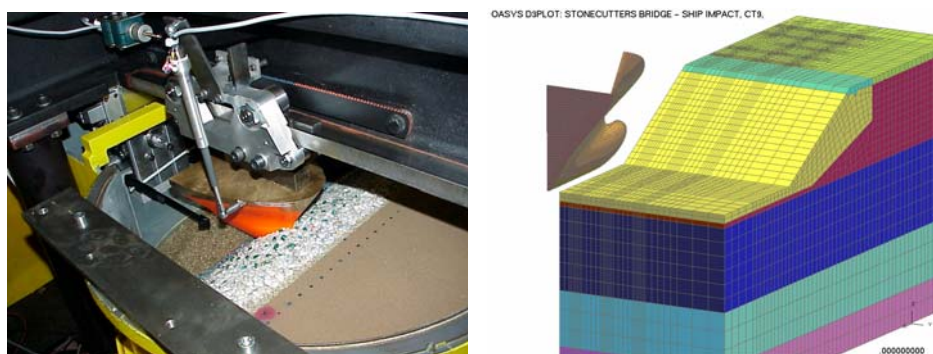
surrounding terrain. Together these studies provided an understanding of the turbulent wind climate resulting from the nearby hills. The measured wind parameters were used to modify the design wind climate presented in the Design Memorandum.

Further wind tunnel studies included a deck section model at 1:80 scale and a high Reynolds Number deck section model at 1:20 scale to check for aerodynamic instability for wind speeds at deck level of up to 95m/sec. Also a 1:100 scale free-standing tower model was tested, and a 1:200 scale full bridge aeroelastic model to confirm the overall behaviour.

Wind buffeting calculations which allow the assessment of the actions on a flexible structure arising from the interaction between gusty winds and the dynamics of the structure were carried out in 2 separate pieces of software to ensure full confidence in the results from this complex analysis.

### **Ship Impact Simulations**

The tower foundations are located approximately 10m behind the seawalls on both sides of the Rambler Channel. Given the close proximity, account was taken in the design for impact loading induced by a ship collision with the seawall. A series of centrifuge tests were carried out to model the effect of a 155,000 tonnes container ship impacting the seawall at a speed of 6 knots. The results of the test including pressure measurements aided calibration of a dynamic 3D finite element model, allowing the force exerted by the vessel impact at the front face of the tower foundations to be determined.



<Fig. 3> Ship Impact Model Test and Numerical Simulation

### **Seismic Studies**

A study of risk levels established three limit states, with earthquake return periods of 120 years for serviceability, 2400 years for ultimate and 6000 years for SILS (Structural Integrity Limit State). The bridge should behave elastically during frequently occurring or minor earthquakes (SLS) without the need for any repair. During a moderate earthquake (ULS) certain elements may undergo large deformations in the post elastic range without substantial reduction in strength, and damage level shall be minimal with repair carried out without the need for bridge closure. The deformation and damage during a severe earthquake (SILS) shall not be such as to endanger emergency traffic or cause loss of structural integrity but might require closure of the bridge for repair. The design earthquake ground motion is represented by site-specific design response spectra (with 5% damping) determined by a Probabilistic Seismic Hazard Assessment (PSHA) for the three return periods.

The PSHA combined the seismic source zoning, earthquake recurrence and the attenuation relationships to produce “hazard curves” showing levels of ground motion and associated annual frequencies of being exceeded. Summation of these from all possible magnitude ranges demonstrated the overall frequency of exceedance for each ground motion level.

### **3.3 Other Design Considerations**

The expected fatigue loading in steel deck plate is intense due to the predicted numbers of heavy goods vehicles. The bridge is located in a sub-tropical climate with summer time temperatures frequently above 30°C. The reduction in stiffness of asphalt surfacing at high temperatures means that the benefit of the surfacing in acting compositely with the deck plate to reduce local stresses will be limited. To cope with this loading, without beneficial composite action with the surfacing, the orthotropic steel deck has been designed with an 18mm thick deck plate and 325mm deep, 9mm thick trough stiffeners.

The construction sequence needed to be taken into account in the design analysis. The concrete back spans were to be constructed in advance of the cantilevering of the main span deck. Full support was to be provided using falsework prior to installation of the stay cables, since without the stay cables the spans are not self-supporting. The back spans provide stability and resistance to the buffeting wind loads on the main span cantilever.



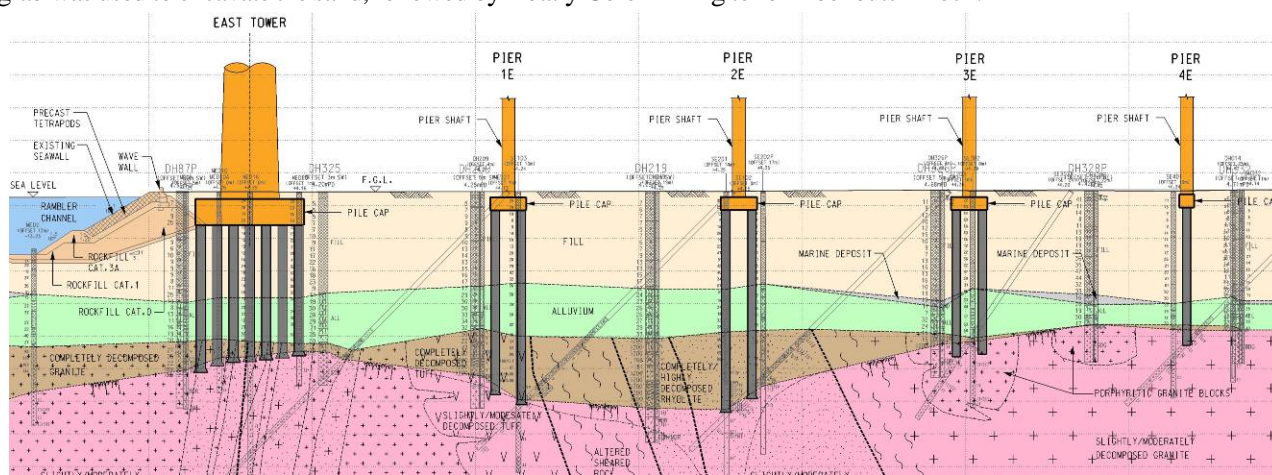
## 4. CONSTRUCTION

### 4.1 Foundations

#### Piles

The ground is reclaimed, with fill overlying alluvial deposits on top of bedrock, typically between 50 and 90m below ground level. However, two major faults running through the site result in some local areas with very deep bedrock, and widely varying levels of bedrock in close proximity.

Cast-in-place end-bearing bored piles up to 2.8m diameter were constructed using 45MPa concrete. Piles lengths are up to 110m, with the bellouts formed at the base up to 4.5m diameter to limit the stresses imposed on the rock. The piles were constructed to tight positional and verticality tolerances using full depth temporary steel casings installed using an oscillator. A grab was used to excavate the sand, followed by Rotary Core Drilling to form bellouts in rock.



<Fig. 4> Foundations – East Side

#### Pilecaps

Constructing the pile caps in the permeable sand next to the sea required careful design of the sheet pile cofferdams and dewatering systems. The back span caps, typically 19m by 11m by 4m thick, were cast as a single pour. To control differential temperatures insulation was provided to retard heat dissipation. Each tower cofferdam was a 38m by 50m by 10m deep excavation and had three layers of steel struts which were incorporated into the caps. Concrete pours typically 1m thick were used to form the 8m thick caps, with additional reinforcement provided at each layer to control thermal cracking.



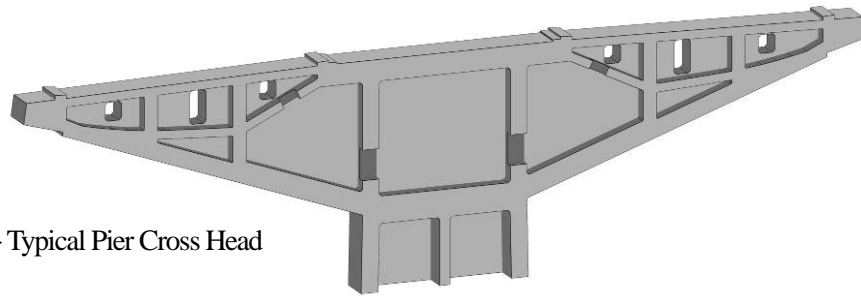
<Fig. 5> Tower Pilecap

### 4.2 Concrete Back Spans

#### Pier Shafts and Cross Heads

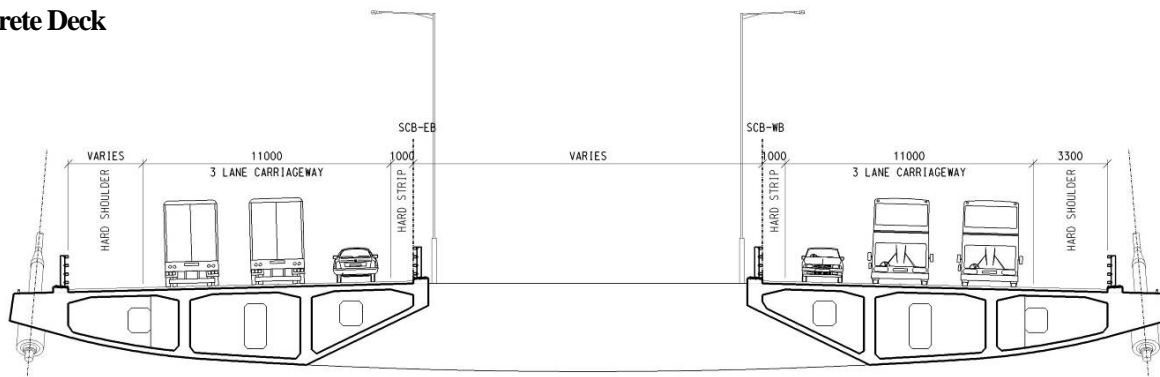
The intermediate pier shafts are between 60 and 65m tall, with hollow box sections tapering from 12.5m to 10m wide, having a constant thickness of 4m. Walls are either 600mm or 1m thick. They were constructed with 60MPa concrete using a hydraulic climbing form system. The end portal shafts were constructed by similar techniques.

At each intermediate pier, the monolithic cross head was formed by in-situ cantilever construction. A temporary works truss cantilevering from the pier shaft provides the support in the temporary condition before the concrete has gained the required strength.



<Fig. 6> Typical Pier Cross Head

## Concrete Deck



<Fig. 7> Concrete Deck – East Back Spans

There are 3 cross girders in each span which were cast first as independent units. After the first stage of transverse prestress was applied, the two longitudinal deck bays between these cross girders were cast. Once the remaining transverse prestress, the final deck pours stitched the span concrete to the pier cross heads. After a continuous deck was formed, the longitudinal prestress which is a combination of internal and external tendons of varying lengths, was applied, with stressing taking place at the ends of the deck where there is adequate access.

This sequence allowed independent components of the deck to be constructed and adjusted to the correct geometry prior to forming an increasingly complex non-determinate structure.



<Fig. 8> Back Spans under construction



### 4.3 Towers

The concrete lower towers have a tapering shape reducing from an elongated circular section 24m by 18m at the base to a 14m diameter at deck level and 10.9m diameter at +175m. The wall thickness is a constant 2m up to deck level, and then tapered to 1.4m at +175m.

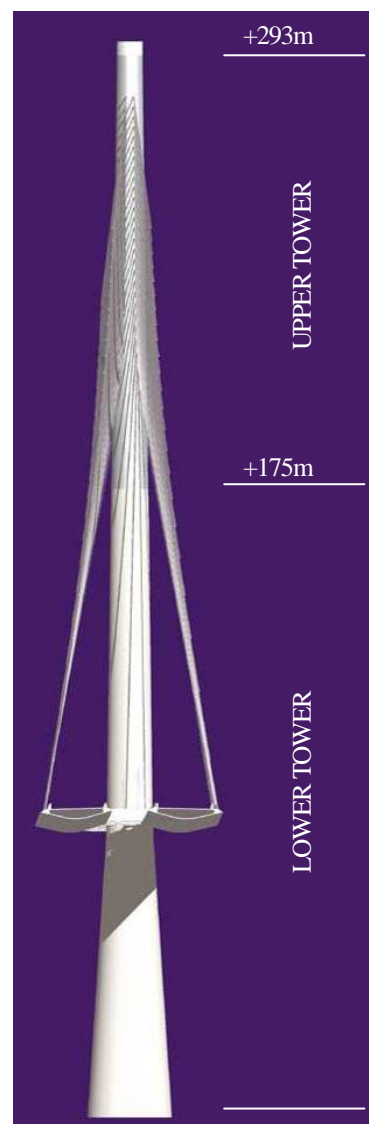
The complex shape was formed using a climbing formwork system. 10 individual panels carried the plywood shutters. Strips were cut off the edges to reduce the perimeter length for each pour. The high quality plywood had to be durable enough for the repeated pours, but also flexible enough to be bent into the ever decreasing radius shape.

The climbing operation to raise the form in preparation for the next pour was controlled by 10 pairs of screw jacks, supported on the top of the previous construction joint. A cycle time 7 days was achieved for the typically 4m high pours, with concrete finishing works done from trailing platforms hanging below the main working platforms.

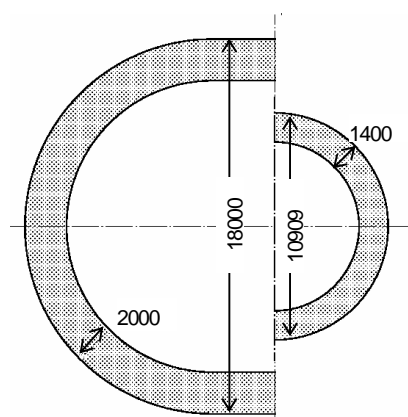
The structure of the composite upper towers is considerably more complex. The circular section has a constant taper from 10.9m diameter at +175m to 7.16m diameter at +293mPD. The outer skin is a 20mm thick structural stainless steel shell. This is composite with a concrete wall, which tapers from 1400mm to become a constant 820mm thick. The lowest 3 sets of stay cables anchor in corbels on the inside face of the concrete wall, whereas the remaining 25 sets anchor within a steel box section forming the core of the tower.

In each tower, 32 stainless steel skin sections make up the outer shell and 25 carbon steel anchor box sections stretch from +195m to +280m. The geometry of the steelwork was carefully controlled in the fabrication process by trial assembly to ensure that when placed on site it fitted into place. Steelwork was lifted into place by the tower crane with site connections being bolted.

The East and West Towers were structurally completed in November and December 2008 respectively, followed by the installation of tower top glazing structure and the maintenance unit.



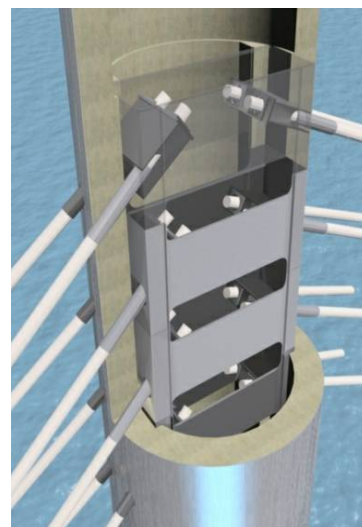
<Fig. 9> Tower Elevation



<Fig. 10> Lower Tower Sections

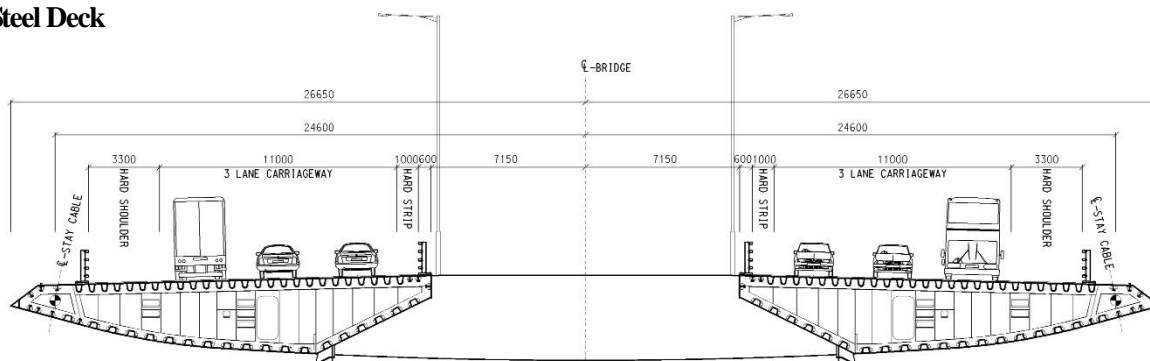


<Fig. 11> Lower Tower Construction



<Fig. 12> Upper Tower

#### 4.4 Steel Deck



<Fig. 13> Steel Deck

#### Fabrication and Assembly

Steel deck panels were fabricated in Shanghaiguan in North Eastern China and assembled into deck segments in Shatian, Guangdong province, Southern China. Match fabrication to ensure a consistent cross section shape and correct segment alignment was crucial to ensure site welding the segments together in Hong Kong proceeded without problems.

#### Heavy Lift

The 88m length of steel deck around each tower is above land and was erected using a heavy lift scheme. In a 4000T lift, the two longitudinal girders were strand jacked simultaneously 75m into their final positions. Due to the tapering tower shape, the two decks were 12m further apart at ground level than in their final positions, so had to be slid transversely once at high level. A 2m longitudinal slide was also necessary to place the decks onto a temporary interface truss before lifting and welding the connecting cross girders, and casting the 2m section to stitch the steel and concrete decks together.



<Fig. 14> Heavy Lift

#### Main Span Erection

Main span deck segments were erected by cantilevering out from each tower. Each 18m long, 53m wide segment comprises the twin deck with connecting cross girder and weighed around 500T. One of the main project constraints was the need to maintain the flow of shipping unhindered by the construction of the bridge. Simulations of shipping movements and measurements of the currents were made. A dynamic positioning barge delivered each segment and used GPS to accurately maintain the position prior to lifting. A rapid lifting speed was key, so the lifting frames at deck level were equipped with high capacity winches which raised each segment 75m into place in around 40 minutes.

Due to the different support conditions there was a geometric mismatch between the lifted segment and the deck cantilever tip, which had considerable transverse sagging. A temporary bowstring prestress arrangement was installed on the lifted segment to manipulate the shape accordingly. Once in place, welding to the previous segment and installation of the stay cables followed. An 8-day target for each cycle was set, meaning that a segment was lifted on either side every 4 working days.

#### 4.5 Stay Cables

The parallel wire stay cables were fabricated to set lengths by Nippon Steel in China. They arrived on site on large diameter drums. Short cables were unreeled at ground level, but most were lifted on their reels to the deck where unreeling took place. A minimum bending radius of 25 times the radius of cable was adopted during site operations to avoid damage.

Stressing was performed using a large hydraulic jack, below deck level, with the jacking equipment transported along on an underslung gantry. Temporary measures to control cable vibrations were used until installation of internal hydraulic dampers to achieve the required level of damping.

#### **4.6 Main Span Closure**

Following installation of the longest stay cables, the deck closure segments were successfully lifted into position in March 2009, marking the achievement of an important milestone before the final completion. Two closure units, one for each of the main girders were 5.3m long and 20m wide, weighing 70 tonnes each. The lifting operation was carried out in the early morning as a result of the temperature control requirements for the bridge geometry and the closure gap. Both closure segments were lifted from the barge simultaneously by one deck lifting gantry. It took less than half hour for the two closure segments to reach the deck soffit level. Following final positioning of the closure segments and adjustments to the bridge alignment, the welding of the erection joints was carried out to link the bridge deck as a whole. A deck closure ceremony was held in April 2009 to celebrate the structural completion of the bridge.



<Fig. 15> Main Span Closure

#### **5. CONCLUSION**

The design and construction of Stonecutters Bridge has posed many challenges which have all been successfully overcome. Realising the vision of Highways Department has taken almost 10 years. Strong emphasis on aesthetics was placed on Hong Kong's first major bridge in a prominent urban setting, visible from many parts of the territory. Procuring the concept through an international design competition ensured a unique and fitting structure was chosen.

Comprehensive studies and analysis were carried out during detailed design to ensure structural safety without excessive use of materials and resources. The wind climate was dominant in the design and a thorough understanding of the wind's effects was vital. Innovative studies into ship impact and seismic loading amongst others were also carried out.

Construction activities were all on a large scale. Deep piles, large concrete pours and massive temporary works have been implemented. Offsite steelwork fabrication was carefully controlled to ensure that components positioned by lifting operations on site fitted to the correct overall geometry. Stonecutters Bridge will be a lasting landmark for Hong Kong.

#### **6. ACKNOWLEDGEMENT**

This paper has been published with permission from Highways Department, HKSAR Government.

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